



# **Starshade Technology Working Group (STWG): Input to the K-T Matrix**

April 20, 2017

Lead: Stuart Shaklan

Jet Propulsion Laboratory, California Institute of Technology

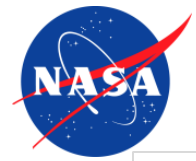
Members: Doug Lisman, Steve Warwick, Jeremy Kasdin, Bertrand Mennesson,  
Brendan Crill, Nick Siegler  
([habexstwg@jpl.nasa.gov](mailto:habexstwg@jpl.nasa.gov))



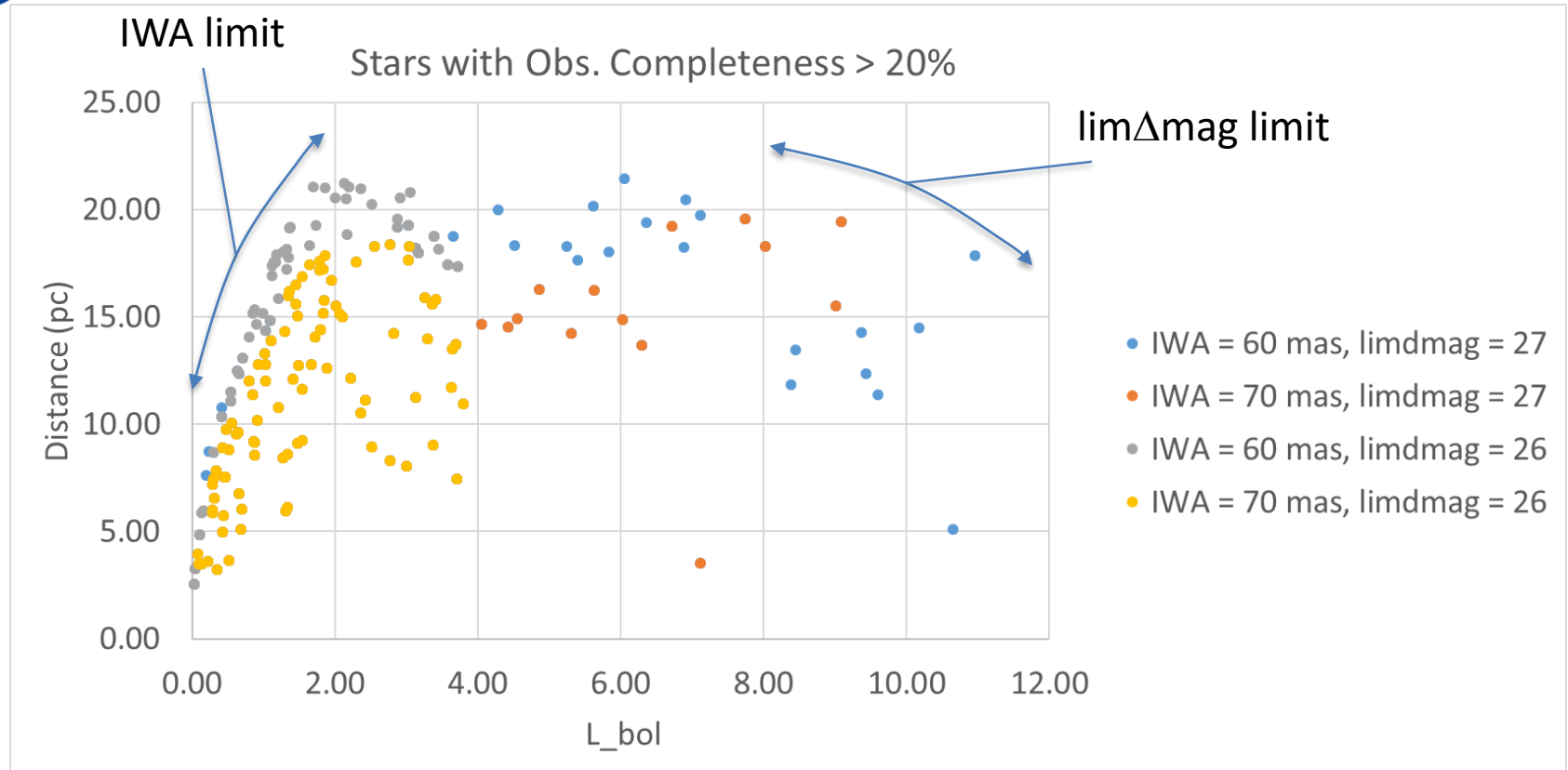
# Architectures and Shape



- There are presently two architectures under study:
  - Central disk and petals
  - Telescoping booms
  - There are indications that 70+ m diameter shades can be made to fit in a 5 m faring for both architectures.
- “Numerically optimized” and “Hypergaussian” share the same characteristics for HABEX:
  - Planets can be observed between petals, but with reduced throughput and more background, requiring tighter tolerances, compared to planets at and beyond the planet tips.
  - Longer petals achieve better IWA for a given diameter.
  - Broad band: the numerically optimized design works over 300-1000 nm and can be made to work at even shorter wavelengths (like the HG) if desired, with little to no increased diameter.



# IWA and $\text{lim}\Delta\text{mag}$



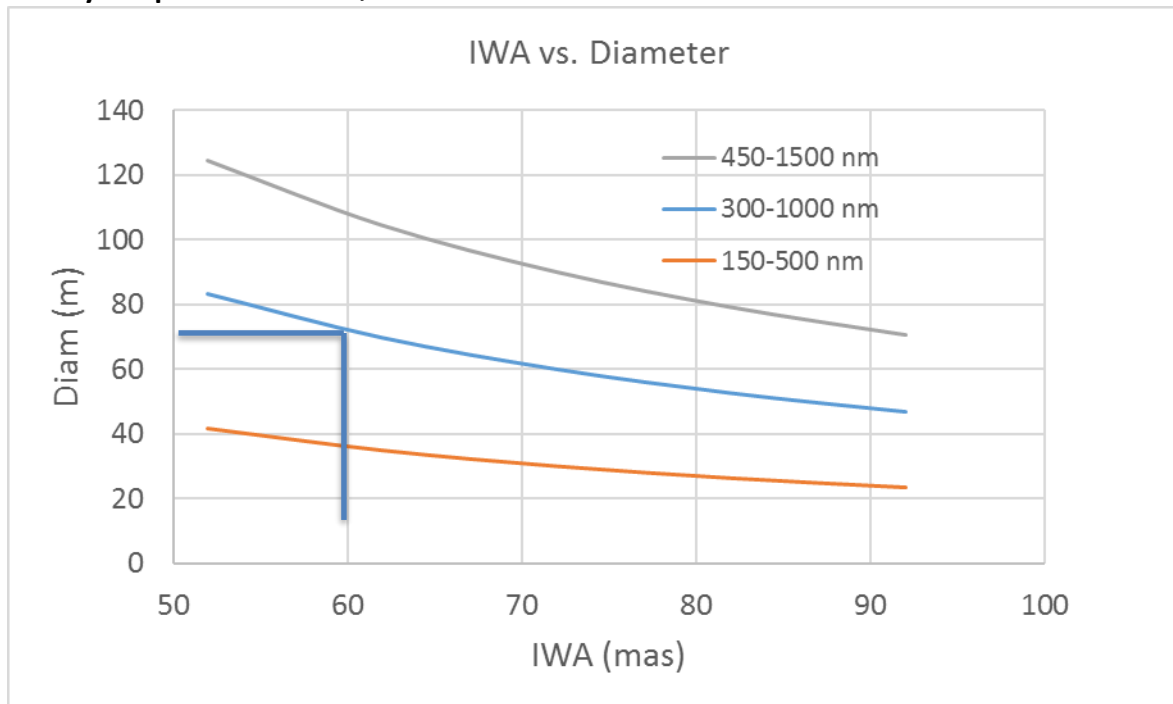
- Smaller IWA generally brings in lower luminosity and more distant stars.
- Deeper limiting sensitivity brings in higher luminosity stars



# Diameter, Wavelength, IWA trade



- Diameter, distance, wavelength and IWA are tied together:
- Fresnel number  $F = r^2 / \lambda Z = r \cdot \text{IWA} / \lambda \sim 10$ .
  - The longest  $\lambda$  in the bandpass matters most.
- Short upper  $\lambda$  (e.g. for detection): increase  $Z$ , improve IWA, but longer  $Z$  requires more fuel and more time to move the starshade.
- Likewise, increase upper  $\lambda$  for characterization, starshade moves closer and is more easily repositioned, but IWA suffers.

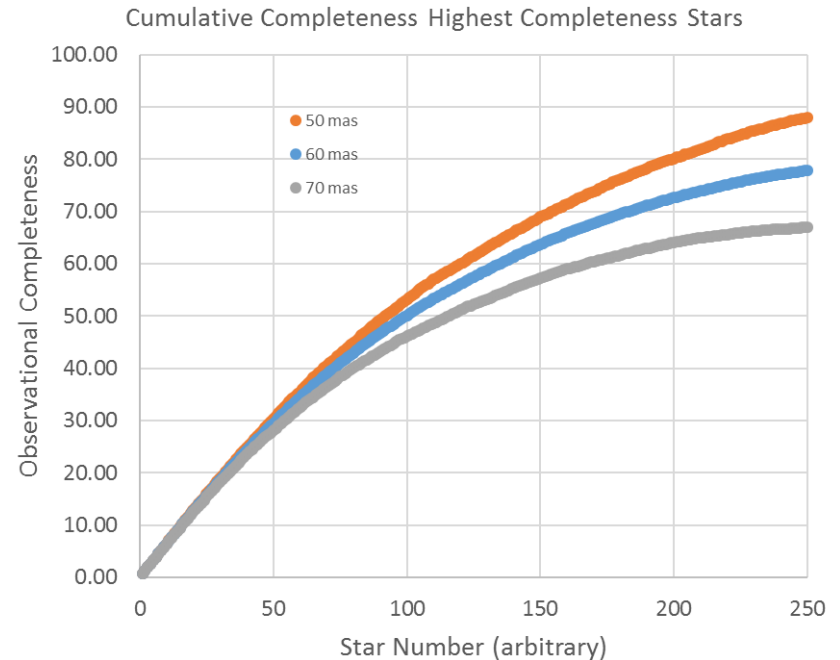
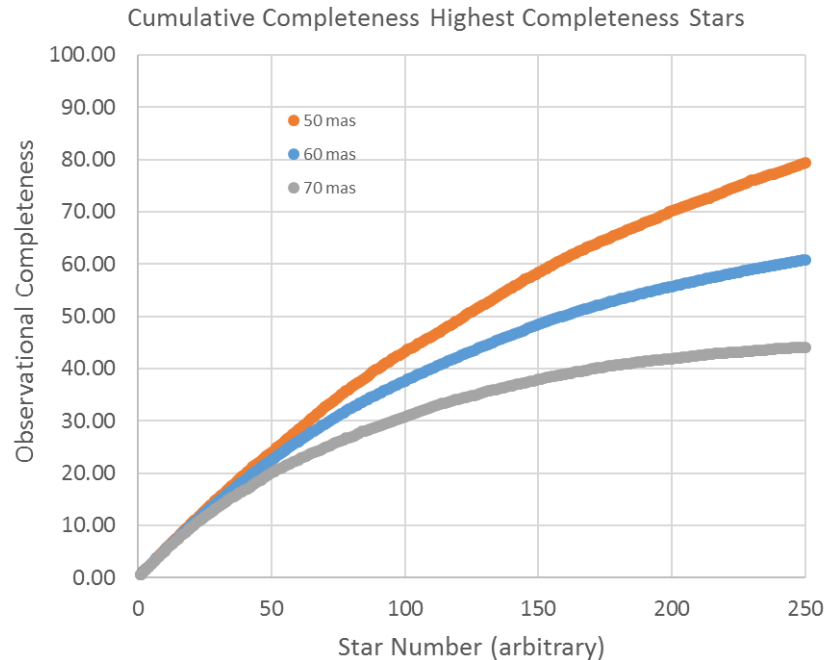




# Why 60 mas?



Achieves 50 HZ with 150 targets and max  $\lim\Delta\text{mag}=26$



$$\lim\Delta\text{mag} = \min(25.5 + 2.5 \cdot \log(L), 26)$$

$$\lim\Delta\text{mag} = \min(26 + 2.5 \cdot \log(L), 27)$$

- At 60 mas, with  $\lim\Delta\text{mag}$  no deeper than 26, achieve CumCompl = 50 HZs with 150 targets.
- Alternatively, with a deeper look to  $\lim\Delta\text{mag} = 27$ , achieve CumCompl = 50 with 120 targets.
- We know from prior studies that in a discovery-only mode, we could observe 30-40 targets per year for 5 years.
- We want to be able to characterize discovered planets – this is challenging if  $\lim\Delta\text{mag}=27$  because integration times get very long.
- Ultimately, optimizing IWA and  $\lim\Delta\text{mag}$  requires extensive “real world” simulations which we plan to carry out with ExoSims.

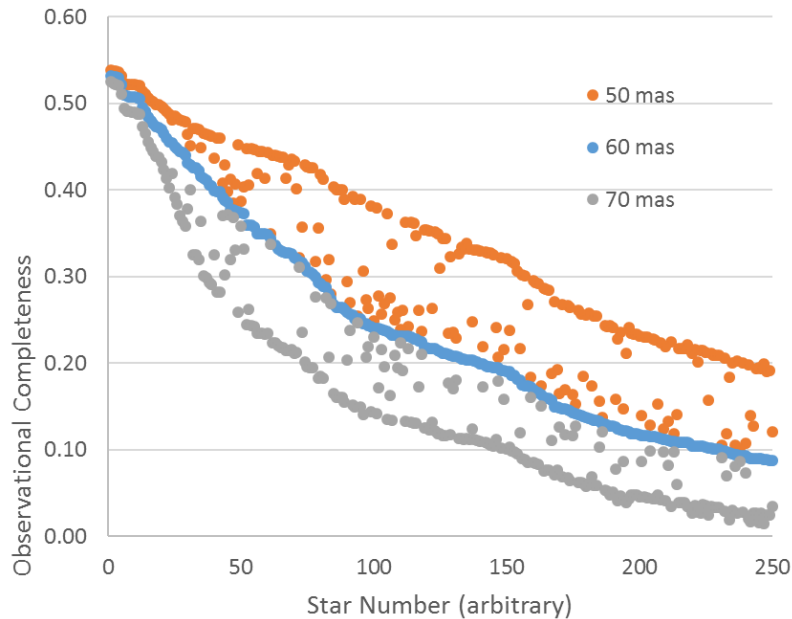


# Why 60 mas?

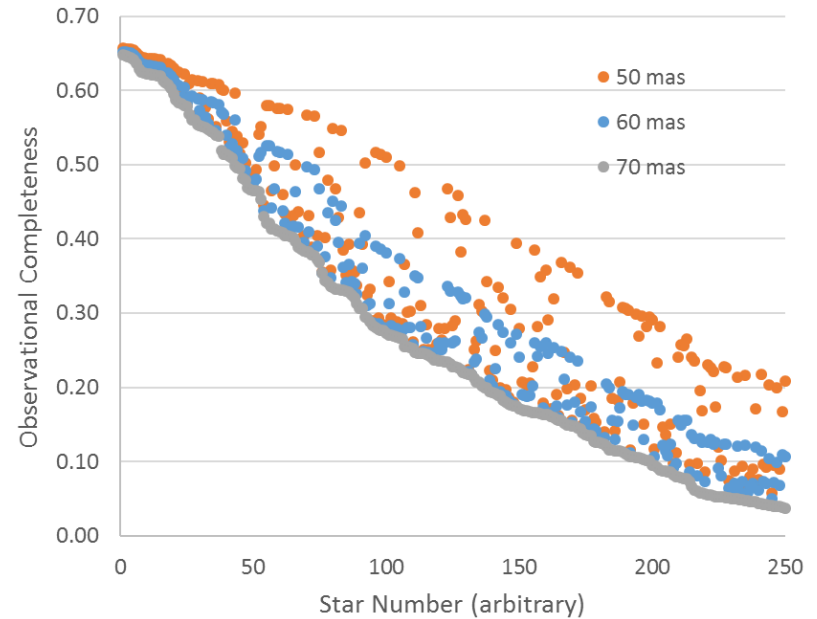


Minimum completeness for 50 HZs is 0.2 with  $\lim\Delta\text{mag}=26$ .

Completeness for Highest Completeness Stars



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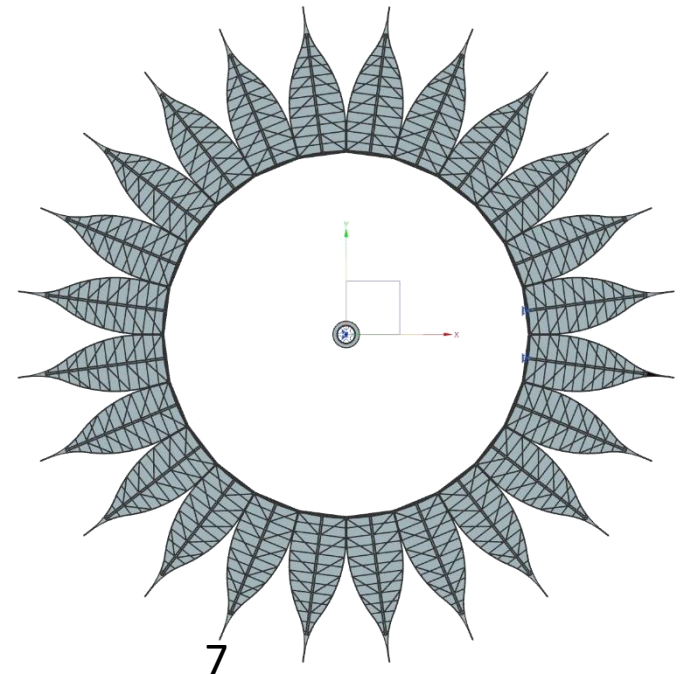
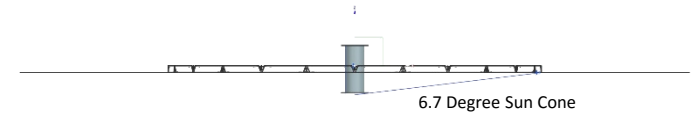
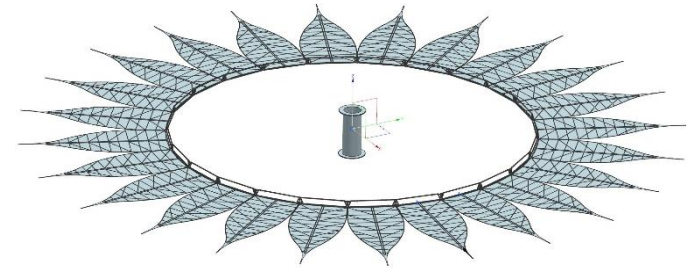
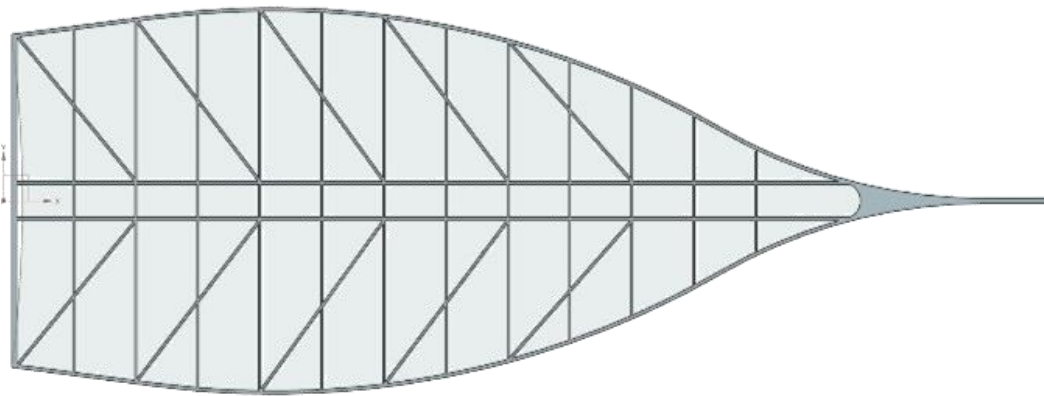
- Minimum completeness is important because it affects the likelihood of reobserving a planet for orbit determination.
- It also impacts the length of characterization observations and scheduling flexibility for reacquiring planets with known orbits.



# 72m-24 Petal Deployed Configuration



- 72m Starshade, qty 24, 16m Petals
- 38" Batten Spacing, battens at truss longerons only, no battens at shorterons
- Spines are 2" wide, separated by 20"
- FEM analysis needed to validate and optimize





# Key tolerances



Design + Tolerances achieves  $1e-10$  contrast at IWA of 60 mas at 1000 nm.

- **Manufacture:**
  - Petal radial position tolerance 0.5 mm (global)  $C=1.2e-11$
  - Edge segment shape errors: 170  $\mu\text{m}$  (3 sigma),  $4.2e-11$ , 30  $\mu\text{m}$  (global)  $C=4.5e-11$
  - Edge placement: 125  $\mu\text{m}$  (3 sigma)  $C=8e-12$ , 14  $\mu\text{m}$  (global)  $C=5e-12$
- **Deployment:**
  - Petal radial position tolerance 0.5 mm (global)  $C=1.2e-11$
  - Petal radial random 1.5 mm (3 sigma)  $C=2e-12$
- **Thermal:**
  - Uniform expansion of truss vs. petal 30 ppm (global)  $C=1.7e-11$
  - Sine wave deformation of petal, 1,2,3,4,5 cycles/petal: 2 ppm (global)  $C=4e-12$
- **Formation Flying:** +/- 1 m lateral motion, +/- 250 km longitudinal motion
- **Not affected by stellar diameter** (exception: alpha Cen A and B)

	Total Mean (Random + Global)						
	300	400	600	700	800	900	1000
<b>Manufacture</b>	5.7E-12	7.9E-12	2.1E-11	2.6E-11	3.0E-11	3.3E-11	3.9E-11
<b>Deployment</b>	2.0E-12	2.5E-12	7.6E-12	9.9E-12	1.3E-11	1.6E-11	2.2E-11
<b>Dynamics</b>	2.8E-14	4.7E-14	1.2E-13	1.5E-13	1.8E-13	2.0E-13	2.2E-13
<b>Thermal</b>	2.3E-13	3.1E-13	4.9E-12	8.9E-12	1.2E-11	1.6E-11	2.5E-11
<b>Nominal</b>	9.5E-13	1.5E-12	8.1E-13	1.8E-12	1.8E-12	1.7E-12	3.5E-12
<b>FF</b>	4.5E-12	3.3E-12	4.4E-12	5.4E-12	2.7E-12	4.9E-12	5.6E-12
<b>TOTAL</b>	<b>1.3E-11</b>	<b>1.6E-11</b>	<b>3.8E-11</b>	<b>5.2E-11</b>	<b>5.9E-11</b>	<b>7.2E-11</b>	<b>9.5E-11</b>
<b>Reserve</b>	<b>8.7E-11</b>	<b>8.4E-11</b>	<b>6.2E-11</b>	<b>4.8E-11</b>	<b>4.1E-11</b>	<b>2.8E-11</b>	<b>4.8E-12</b>

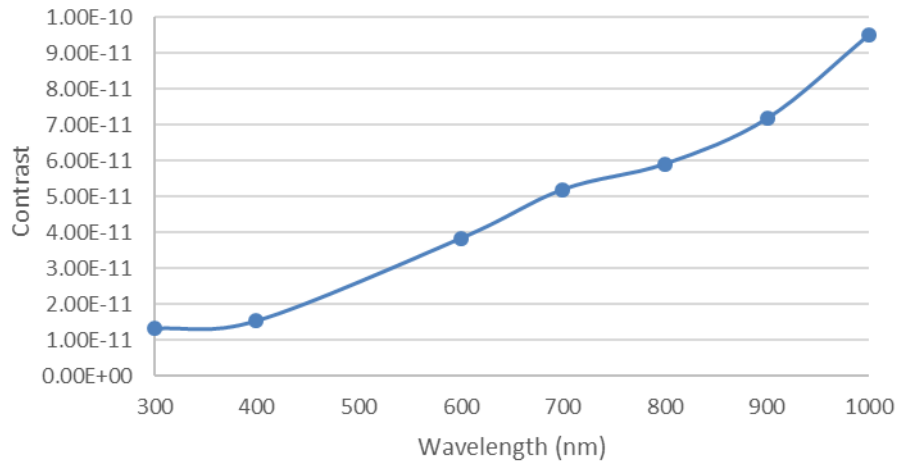




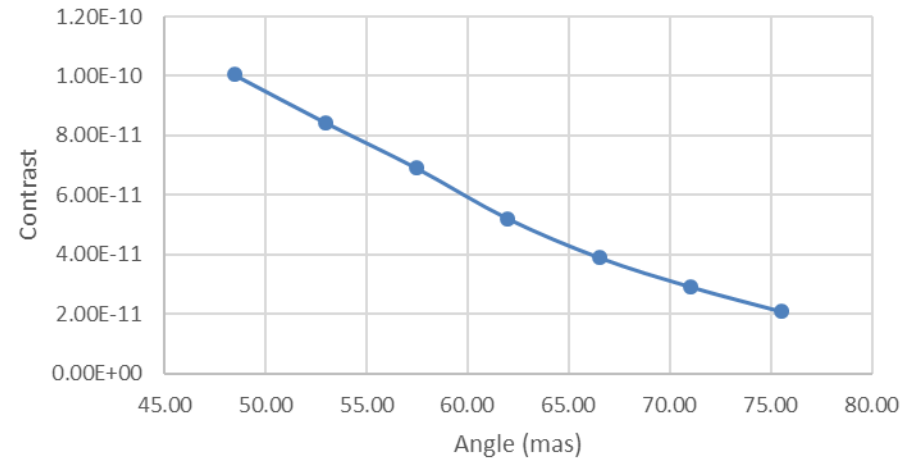
# 72 m starshade

40 m disk, 16 m petals, IWA  $\sim 60$  mas, 300-1000 nm,  
3 mm wide tips

Performance vs. Wavelength, IWA=62 mas



Performance vs. angle,  $\lambda 700$  nm



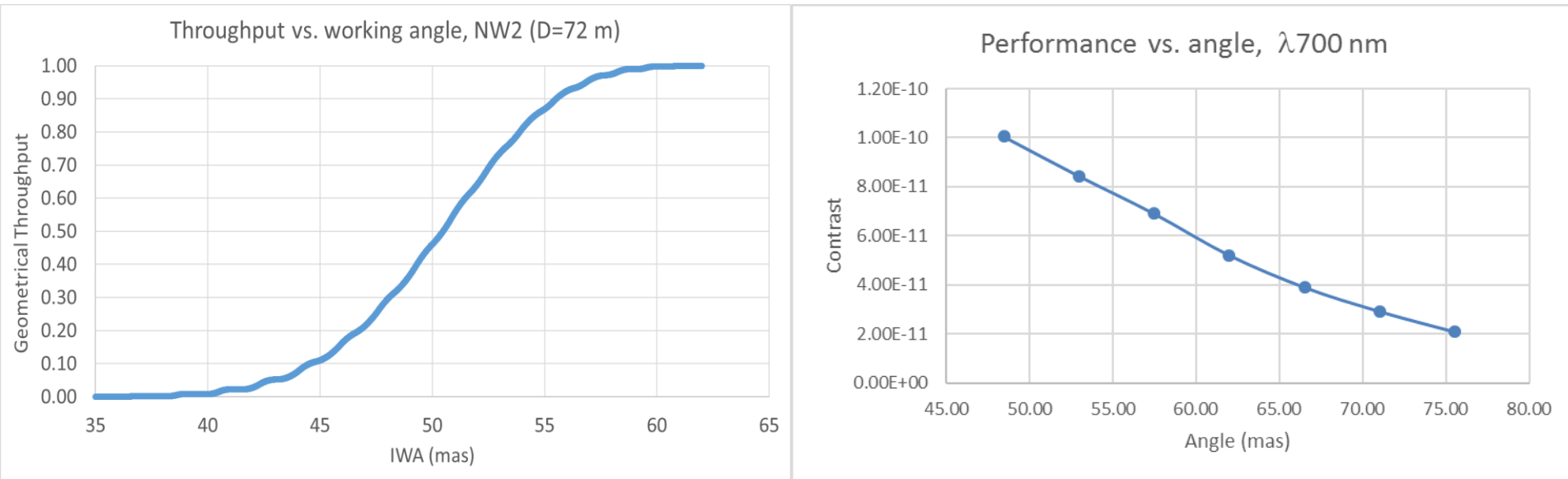
Truss has 0.5 mm global petal manufacturing tolerance (average value of manufactured vs. ideal radius).  
Truss has 0.5 mm global deployment tolerance.  
Truss vs. petals have thermal strain ( $CTE \cdot dT$ ) tolerance of 30 ppm.

The starshade tolerancing looks reasonable and shows that we can expect the contrast at the IWA to be  $1e-10$  and to improve as we move radially away from the IWA, and to worsen as we move inboard of the IWA.



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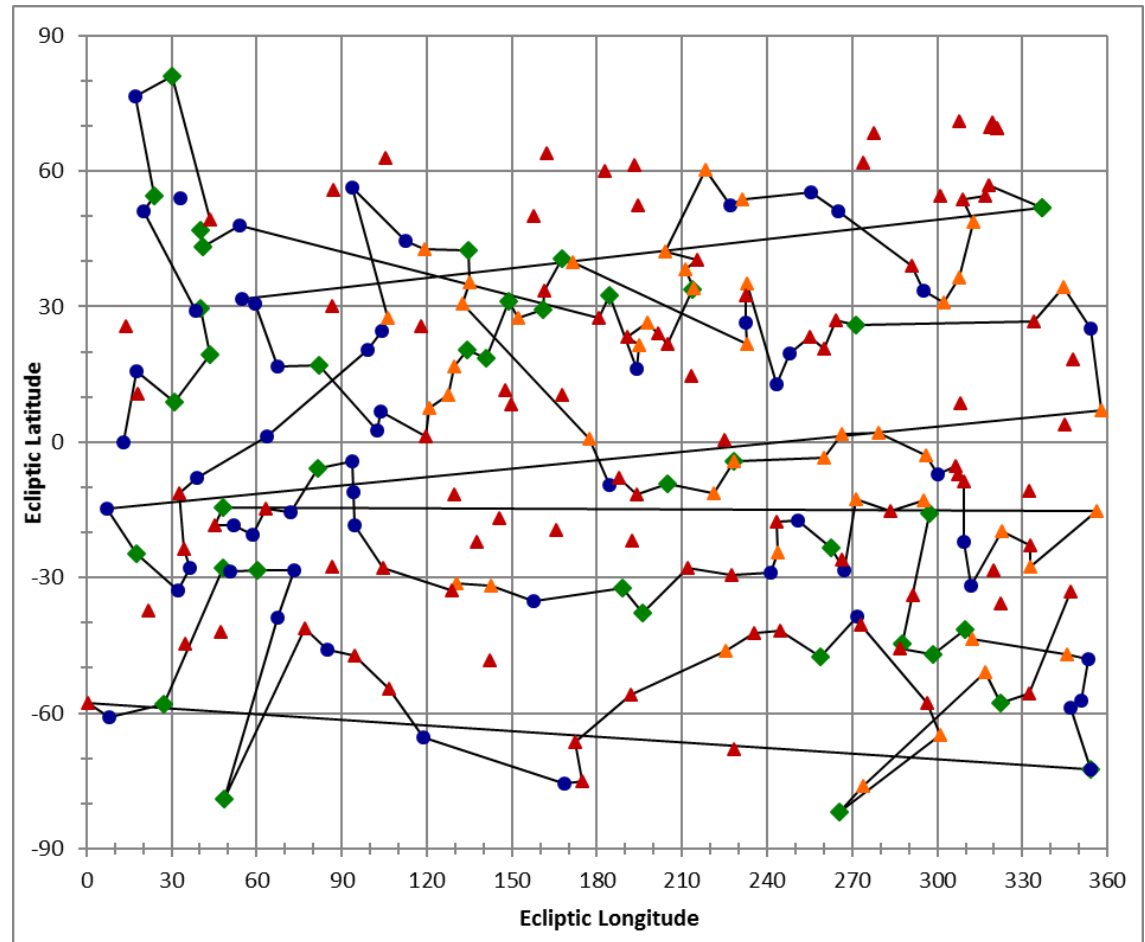
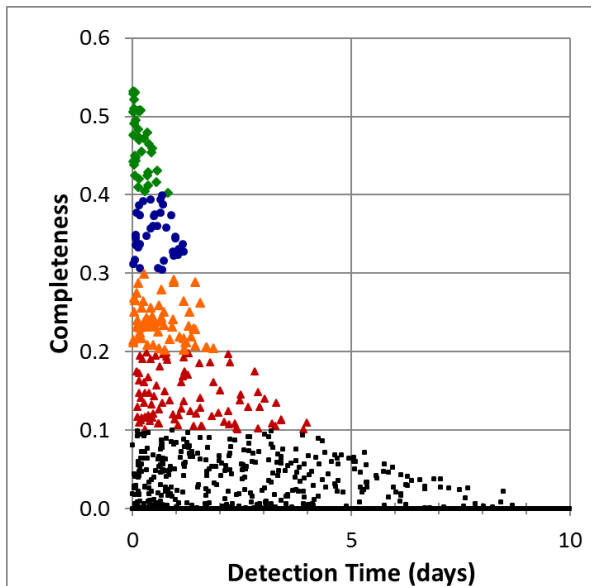
The starshade tolerancing looks reasonable and shows that we can expect the contrast at the IWA to be  $1e-10$  and to improve as we move radially away from the IWA, and to worsen as we move inboard of the IWA.



# 5 Yr Discovery-only sequence



- This chart shows the sequence of observations for a 5 year mission aimed at discovering Exoearths. Overhead is 8 hours.
- This was “optimized” by hand using a spreadsheet.
  - No revisits
  - Forced to obey acceleration limits and solar avoidance (40-83 deg).
- Generally worked from high to low ecliptic latitude from year to year.
- Cumulative completeness was 53 HZs
- Total delta-V was 18,000 m/s

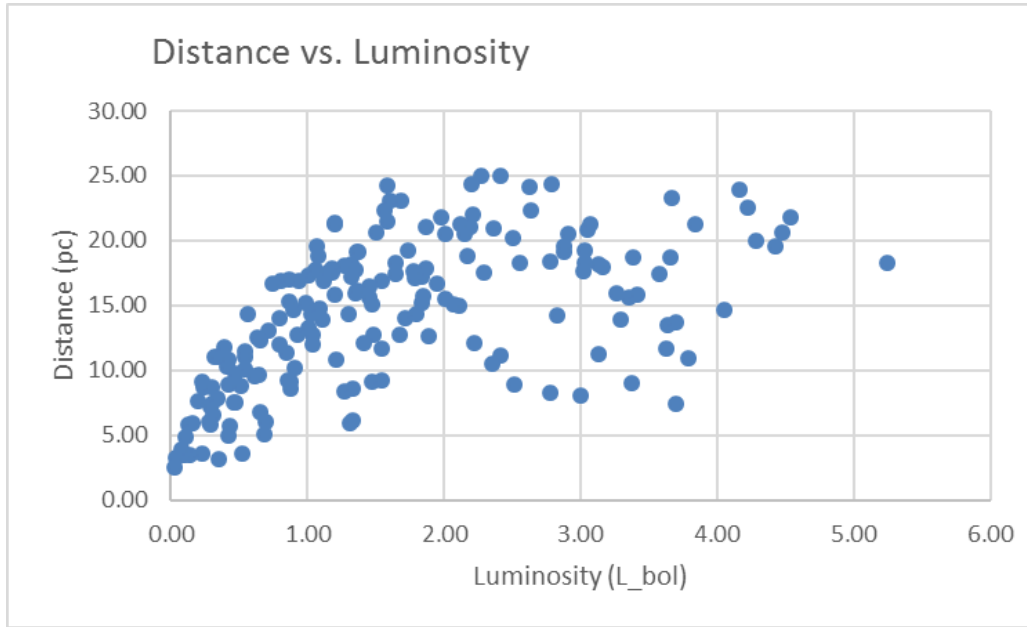


$$\lim \Delta \text{mag} = \min(25.5 + 2.5 * \log(L), 26)$$

Credit: Amy Trangsrud, JPL



# 5-Yr Discovery Sequence Observed Targets



Spectral Class	Number of Targets
M	3
K	34
G	61
F	85
A	1

- Distribution of spectral class favors high luminosity stars.
- Chris Stark sees a similar distribution in his model.
- Is this the kind of distribution we want?
  - We need better IWA to sample more K stars.



# Starshade Parameters for DRM Study



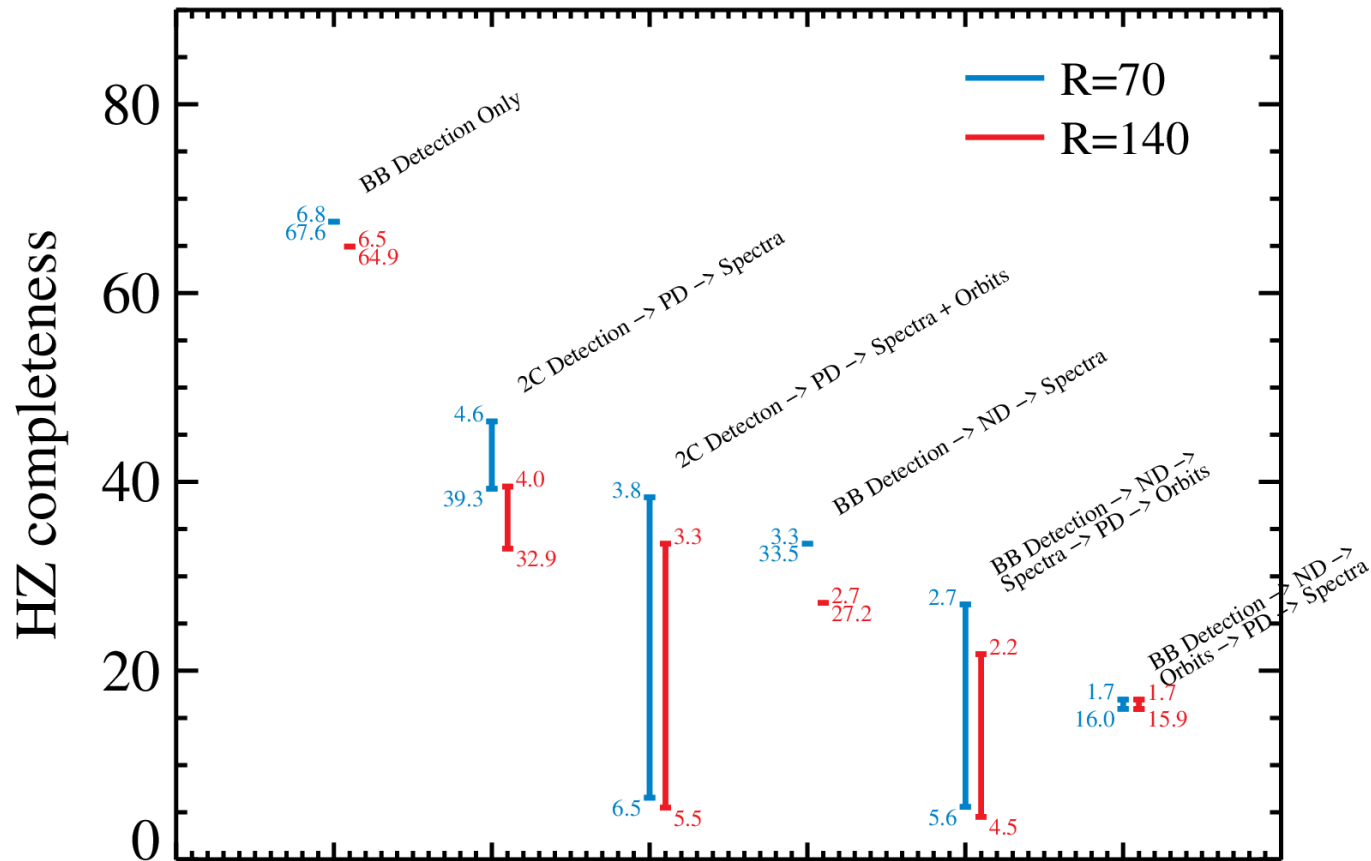
<b>Starlight Suppression Systems:</b>			
<b>Starshades</b>			
<b>Starshade #1 (S1, Large one)</b>			
starshade diameter tip to tip		72m	
occultor initial wet mass		6000 kg	let's try 8000 kg as well, i.e 4T of fuel instead of 2T.
occultor initial dry mass		4000 kg	including the bus and 30% contingency
nominal starshade distance		124 Mm	corresponds to 60 mas IWA over [blue edge ;red edge]
starshade blue edge at nominal distance		300nm	
starshade red edge at nominal distance		1000nm	
IWA at nominal distance		60 mas	applies to all wavelengths btw blue and red edges
Second (shorter) starshade distance ?		Yes	Optional (see observing method) - Only if some Earth-twin is detected far enough
Second starshade distance		Star dependent	to be characterized up to IR wavelength $\lambda_{IR}$ , with IWA / $\lambda_{IR}$
			See observational approach
<b>Starshade #2 (S2, Small one, detection only)</b>			
starshade diameter tip to tip		32m	or is it 35m?
occultor initial wet mass		3500 kg	check with Doug
occultor initial dry mass		1500 kg	
nominal starshade distance		55 Mm	
starshade blue edge at nominal distance		400nm	
starshade red edge at nominal distance		500nm	
IWA		60 mas	applies to all wavelengths btw blue and red edges
<b>For both starshades:</b>			
settlingTime		2 hours	1 h for final acquisition + 1 hour for final setup/"settling" (from Doug)
Total occultor slew thrust		1N	1N for 2 ARRMM Hall effect thrusters; or 0.5N for 2 NEXT Ion Thrusters
occultor slew Isp		3000s	specific impulse (3000s for ARRMM, 4000s for NEXT)
Default contrast to use at IWA (if no curve provided)		10-10	
Telescope spacecraft mass		5800 kg ?	Does not affect relative dynamics
occultor station keeping Isp		308s	specific impulse for bi-prop
default burn portion for slew		< 75%	(ExoSIM only?)
Efficiency of station keeping fuel use		0.8	
Overall-end-to-end throughput (excluding QE)		0.7	includes all optics transmission
Core throughput in photometric aperture	0.69	0.69	as should be for a perfect Airy pattern & for planet outside of IWA. 0 otherwise.
User provided throughput curve (1D)			Same definition as for coronagraph, follow yield standard guidelines located at: or use step function wrt geometric IWA
User provided stellar suppression curve (1D)			Same definition as for coronagraph or use step function wrt geometric IWA



# Chris Stark's DRM Results



Single Starshade:  $m_{\text{tot}}=6000$  kg



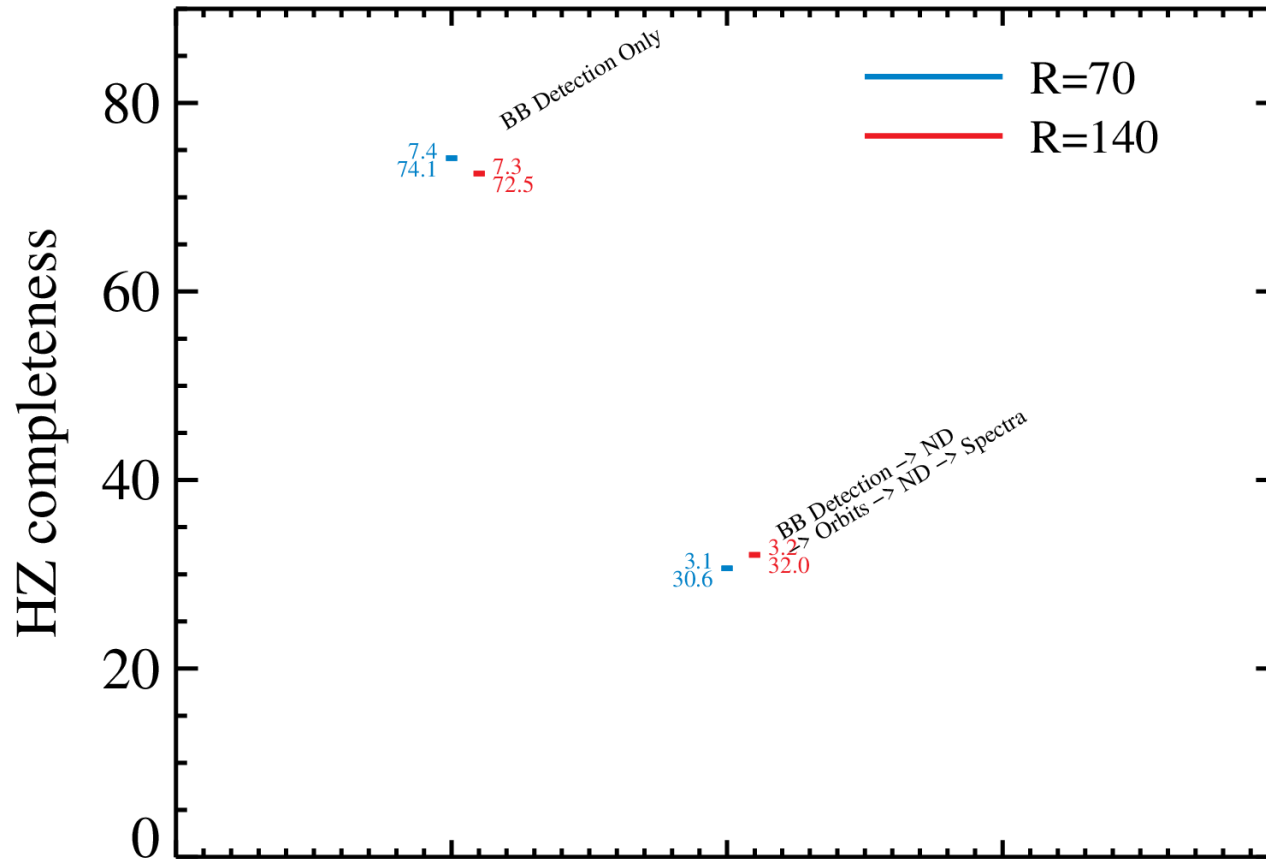
PD = Perfect Differentiation of all planet types and background objects  
ND = No Differentiation of detected objects/complete confusion



# Chris Stark's DRM Results



2 SS |  $m_{\text{tot}} = 3500$  | Detection w/ IFS

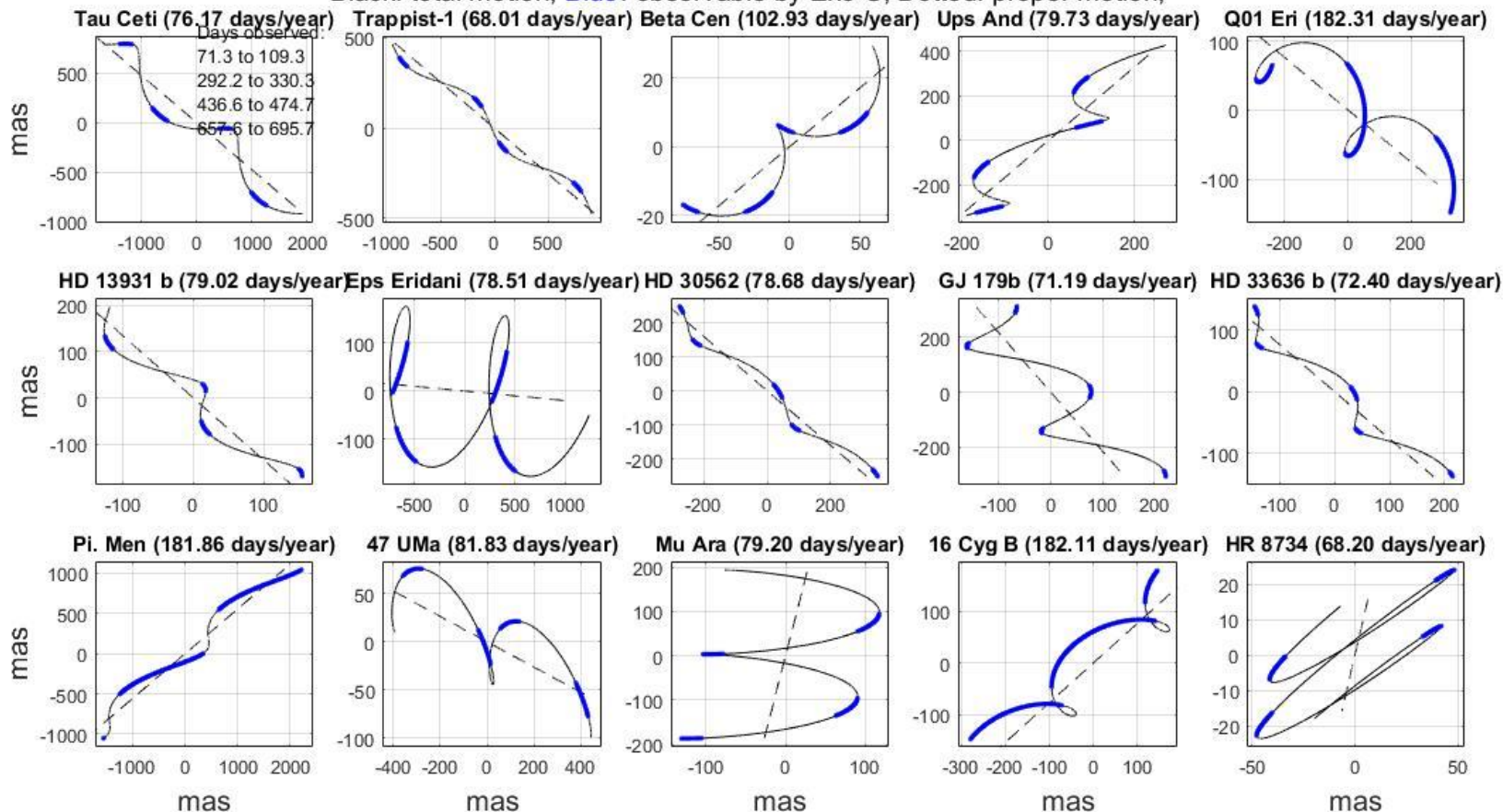


PD = Perfect Differentiation of all planet types and background objects  
ND = No Differentiation of detected objects/complete confusion

# PPM in observing windows

EXO-S. FROM: 2028, DAY 0.00 TO 2030, DAY 0.00

Black: total motion; Blue: observable by Exo-S; Dotted: proper motion;



Solar angle restriction 56-83 deg. Two years shown.

HABEX PSF will be ~25 mas. Some targets can be disambiguated from background in 10 days. (Credit: Sergi Hildebrandt, JPL)





# Must observe alpha Cen A, B?



- Need two starshades?
  - In IR might be feasible to use coronagraph for one star while blocking light of the other with the SS.
    - Talk to Rus Belikov who has put a lot of thought into this.
  - HZ angle  $\sim 350\text{-}1000$  mas
    - That's  $14\text{-}40 \lambda/D$  in the visible,  $7\text{-}20$  at  $1 \mu\text{m}$ .
  - Rus favors the idea of using the DMs w/o a coronagraph to control scatter from the off-axis component, while the starshade observes the on-axis target.
- Large + small starshade
  - Small one is only for blocking light, can be high Fresnel number, large IWA.
- If two starshades used simultaneously, need to modify the camera to do formation flying.



# Risks for Starshade Technology and Yield



- RCT1: Starlight suppression performance is degraded (e.g. formation flying issue, petal shape or deployed position is sub-optimal, etc)
  - First effect is to increase integration time at the long wavelength end of the bandpass.
    - Integration times increase linearly with instrument background (once it is the dominant noise source).
    - Background increases as the square of the defect parameter (e.g. petal position).
  - Impact is low for detection, where integration times are short.
  - A mitigating approach could be to move the defect (if local) away from the position of the planet to minimize noise during characterization observations.
    - But baseline design is to spin the starshade. Not spinning could introduce significant thermal effects.
- RCT2: low value of  $\eta_{\text{Earth}}$  ( $\leq 0.1$ )
  - Obviously this is a big deal because the observational completeness is so low.
  - There will still be many other types of planets discovered
  - We could attempt to make very deep observations to find smaller (and presumably more abundant) planets, at the expense of reducing the number of targets observed.



# Opportunities for Starshade Technology and Yield



- OCT1: SM Fiber fed spectrometer provides performance improvement
  - Gain in either bandwidth, IWA or stellar suppression level
  - Gain in throughput relative to IFS
- OCT2: High dispersion Spectrograph relaxes stellar suppression level and starshade requirements
- OCT3: High  $\eta_{\text{earth}}$  value ( $\geq 0.3$ ) increases yield
- OCT4: High completeness per observation, from small IWA and superior contrast, increases characterization of a priori Earths.
- OCT5: Use starshade at working angles between petals, e.g. 50 mas for a starshade with tips at 60 mas.



# Conclusions



- The starshade can achieve small IWA (60 mas), deep contrast (limDmag > 26), broad band (300-1000 nm), with high throughput (no loss at starshade) and make > 150 observations over 5 years.
- Preliminary designs show that a sufficiently large starshade (72 m) could be packaged in a 5 m faring.
  - Easily fits in SLS.
- If operated in discovery-only mode, realistic DRMs show that it achieves Program Completeness > 50 HZ
- Requirements to do background disambiguation and orbit determination will have a significant impact on completeness.
- A starshade in conjunction with a coronagraph, or a 2-starshade mission (one could be small) would enable deep observations of alpha Cen A and B, and other binaries.